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Strain control of composite superconductors to prevent degradation of superconducting magnets due to a quench. I. $Ag/Bi_2Sr_2CaCu_2O_x$ multifilament round wires

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Abstract

The critical current of many practical superconductors is sensitive to strain, and this sensitivity is exacerbated during a quench that induces a peak local strain which can be fatal to superconducting magnets. Here, a new method is introduced to quantify the influence of the conductor stress and strain state during normal operation on the margin to degradation during a quench, as measured by the maximum allowable hot spot temperature $T_{\text{allowable}}$, for composite wires within superconducting magnets. The first conductor examined is Ag-sheathed $Bi_2Sr_2CaCu_2O_x$ round wire carrying high engineering critical current density, J_E, of 550 A/mm^2 at 4.2 K and 15 T. The critical axial tensile stress of this conductor is determined to be 150 MPa and, in the absence of Lorentz forces, $T_{\text{allowable}}$ is greater than 450 K. With increasing axial tensile stress, σ_a, however, $T_{\text{allowable}}$ decreases nonlinearly, dropping to 280 K for σ_a = 120 MPa and to 160 K for σ_a = 145 MPa. $T_{\text{allowable}}(\sigma_a)$ is shown to be nonlinear and independent of magnetic field from 15 T to 30 T. $T_{\text{allowable}}(\sigma_a)$ dictates the balance between magnetic field generation, which increases with the magnet operating current and stress, and the safety margin, which decreases with decreasing $T_{\text{allowable}}$, and therefore has important engineering value. It is also shown that $T_{\text{allowable}}(\sigma_a)$ can be predicted accurately by a general strain model, showing that strain control is the key to preventing degradation of superconductors during a quench.

Introduction

In the last two decades, several superconductors including Cu/N_3Sn wires, Ag/$Bi_2Sr_2CaCu_2O_x$ (Bi-2212) wires, Ag/$Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) tapes, MgB_2 tapes and wires, and REBCO coated conductors have seen significant advances in terms of record critical current density and lengths produced. These advances have fueled many research activities to build powerful superconducting magnets, such as a 3 T, 20 K cryocooled MRI magnet [1], a 28 T solenoid magnet with an insert made using high-temperature superconductors [2], a 26 T all REBCO magnet [3], and a 32 T all superconducting magnet system [4]. With several of these record-achieving systems having been degraded due to quenches, it has become increasingly clear that quench protection is a central issue [5].

A central strategy to building magnets safe from quenches using these conductors is to obtain a fundamental understanding of failure mechanisms of superconductors during a quench. An important practical question along this line is whether quench-induced critical current degradation is driven by strain. Each of these conductors (Nb_3Sn, Bi-2212, Bi-2223, MgB_2, and REBCO) is known to be strain sensitive, and therefore if quench degradation is due to strain, then there is an intrinsic design trade-off between the operating strain, which is due to Lorentz forces and strain associate with magnet manufacturing and cool-down, and the temperature margin during a quench. The question becomes particularly important for high field superconducting magnets, for which the Lorentz forces are particularly large.

Here we introduce a new method to quantify the influence of the conductor stress and strain state during normal operation on the margin to degradation during a quench for composite superconducting wires and apply it to a high current Bi-2212 wire. This method utilizes spiral wound coils on mandrels to determine the critical current of a superconducting wire as well as measure its critical axial tensile stress and simulate a quench with a large current in high magnetic field and an axial stress on the conductor approaching to the critical stress.

Methods

Sample preparation and critical current measurement

Samples are commercial powder-in-tube Ag/Bi-2212 round wires (diameter = 0.8 mm, 37 x 18 filaments (18 bundles, each of which has 37 filaments) (Figure 1), filament diameter ≈ 20 μm, the area ratio Ag:Ag-0.2 wt.% Mg:Bi-2212 = 0.5:0.25:0.25 in which Ag-0.2 wt.% Mg is an oxide-dispersion strengthened alloy) that are available in a single piece of 2.5 km from industry (e.g. the Oxford Superconducting Technology, New Jersey) [6]. High critical current density (J_c) was obtained using a recently developed overpressure partial melt processing (4% oxygen and balance argon, total pressure = 25 bar, oxygen partial pressure = 1 bar) [7,8]. High gas pressure during the heat treatment densifies wires through silver creep and increases the Bi-2212 filament density from ~75% to >92% [9]. A 1 m of such wire is wound on an alumina barrel with spiral grooves (32 mm diameter, 3.175 mm pitch length). The barrel design is similar to those used for measuring critical current (I_c) of ITER Nb-Ti and ITER Nb_3Sn strands [10]. The spiral coil was heat treated and after the heat treatment, the sample was transferred to a G-10 barrel with matching grooves for I_c measurements and quench experiments. The critical current was determined using a standard four-point resistive measurement technique with an electric field criterion of 1 μV/cm at 4.2 K and in magnetic fields up to 31 T. The *n*-value, the resistive transition index, was obtained by fitting the electrical field – current (*E-I)* curve around *E*=0.1-1 μV/cm. The magnetic field was applied parallel to the central axis of the barrel and thus perpendicular to the wire. During I_c measurements, the transport current is oriented such that the Lorentz force pushes the wire inward so that it is supported by the G-10 barrel and experiences zero hoop stress.

Determining the critical axial tensile stress using hoop stress

The critical axial stress at which I_c degrades irreversibly is an important engineering parameter and was determined using the spiral coil as follows. A hoop stress σ_h was induced using a transport current oriented such that the Lorentz force was outward away from the G-10 barrel ($\sigma_h = BJr$, where *J* is the current density averaged over the entire wire cross-section and *r* the radius of the spiral.). The transport critical current was re-measured after applying the hoop stress.

Determining the maximum allowable temperature during a quench, $T_{allowable}$, with increasing axial stress σ_a

The spiral coil geometry lends itself well to simulating a quench with a large current in high magnetic field and thus large Lorentz forces. This is accomplished by applying a controlled hoop stress and initiating a quench using a heater, similar to previous studies on short straight samples [11] and coils [12]. The heater is an epoxy spot heater (Ecobond 60L) designed for triggering small normal zones and it is also easy to mount onto the sample. The normal zone evolution was monitored via thermocouples (E-type, AWG32) and voltage taps around the hot zone. The hot spot temperature was obtained by cross-examining the measured resistivity of the hot zone with the temperature dependence of Bi-2212 wire resistivity [13] and verified by thermocouples. Samples were quenched with raising hot spot temperature incrementally, beginning around 50 K, and after each quench, the I_c of the sample was re-measured with zero hoop stress. The safety margin was measured using the maximum allowable hot spot temperature $T_{allowable}$ during a quench, which is defined as the hot spot temperature at which I_c of the wire degrades by 5%. The simplification of quench degradation limit to $T_{allowable}$ is warranted by our earlier findings that the maximum hot spot temperature T_{max} correlates well with J_c degradation induced by a quench for a large pool of Bi-2212 wires and that the degradation is strain driven [11]. This experiment is representative of quenches in high-field magnets whereas prior quench experiments were performed either without electromagnetic stresses [11] or unknown (and well below 80 MPa) stresses in an epoxy impregnated coil [12,14].

Results

J_c(B) and tensile axial stress limit

Figure 1 shows the 4.2 K engineering current density (J_E) and n-value as a function of magnetic field up to 30 T for our sample. The sample carries an exceptional J_E of 550 A/mm^2 at 4.2 K and 15 T. Figure 2 depicts the results of a critical axial stress measurement at 4.2 K and 15 T. I_c is constant with increasing the hoop stress till 150 MPa, at which irreversible reductions in both I_c (5%) and *n*-value are observed. The decrease in *n*-value indicates that irreversible damages is mechanical and likely caused by filament cracking. The results are consistent with the axial strain dependence of J_c for Ag-Ag-alloy/Bi-2212 wires shown in the Figure 1 inset: J_c is reversible with increasing tensile strain to an irreversible strain limit (ε_{irr}) ranging from 0.45% to 0.6% [15-19], where J_c starts to degrade irreversibly likely because filament breakage becomes significant. This hoop stress technique was used to determine the stress limit of the high-strength Ag/Bi-2223 tape manufactured by Sumitomo Electric and was shown to produce trustable results [20,21].

$T_{allowable}(\sigma_a)$ in magnetic field up to 30 T

Figure 3 shows how I_c of the Bi-2212 coil evolves due to a series of quenches with increasing T_{max}. Note that at 4.2 K, self field, when $\sigma_h = 0$, the $T_{allowable}$ is greater than 450 K (Figure 3). The dependence of I_c on the T_{max} at a constant axial tensile stress σ_a (hoop stress) is determined; one example is presented in Figure 4. The wire carries an I_c of 262 A at 4.2 K, 15 T and survives a quench with T_{max} = 330 K with the Lorentz force pointing inward. The next nine quenches were conducted with a hoop stress of 120 MPa applied and $T_{\text{allowable}}$ drops to 280 K. The hoop stress is then increased to 145 MPa and $T_{\text{allowable}}$ decreases further to 160 K.

We perform experiments similar to that presented in Figure 4 in magnetic fields ranging from 20 T to 30 T using a 31 T high-field resistive magnet facility at the National High Magnetic Field Laboratory (NHMFL). These experiments generate a coherent relationship between $T_{\text{allowable}}$ and the applied axial tensile stress, graphed in Figure 5, which is independent of magnetic field. The relationship is highly nonlinear; $T_{\text{allowable}}$ decreases only from 450 K to 280 K with increasing the stress from zero to 120 MPa, but then decreases quickly to below 160 K for a stress of 145 MPa.

Analysis and discussion

Now we attempt to provide a mathematical description of $T_{\text{allowable}}$ as a function of only σ_a. Fundamental to our analysis is the assumption that quench induced I_c degradation is strain driven. In composite superconducting wires the total strain of superconductor filaments in a composite superconductors, ε_t, during a quench can be described as

$$\epsilon_t = \epsilon_0 + \epsilon_s + \epsilon_q \qquad (1)$$

where ϵ_0 is the strain on the superconductor filaments due to bending and cool-down, ϵ_s the strain from Lorentz forces, and ϵ_q the axial tensile strain from differential thermal expansion between the entire wire and the superconductor filaments during the temperature rise during the quench. ϵ_s results from the operational axial stress σ_a, an important parameter used for magnet design, through $\epsilon_s = f(\sigma_a)$, the inverted stress - strain relationship of the wires [18,22]. We assume that ϵ_q relates to T_{max} only and does not relate to either $\mathrm{d}T_{\text{max}}/\mathrm{d}t$ or $\mathrm{d}T_{\text{max}}/\mathrm{d}x$. In the case of Ag/Bi-2212 wires, ϵ_q in the Bi2212 filaments can be appropriated by

$$\epsilon_q|_{\text{Bi2212 filaments}} = \Delta L/L_{T_{max}-4.2K}|_{\text{wire}} - \Delta L/L_{T_{max}-4.2K}|_{\text{Bi2212 filaments}} \qquad (2)$$

where $\Delta L/L_{T_{max}-4.2K}|_{wire}$ and $\Delta L/L_{T_{max}-4.2K}|_{\text{Bi2212 filaments}}$ the total linear expansion from 4.2 K to T_{max} for the entire wire and the Bi2212 filaments, respectively. Combining equation (1), $\epsilon_s = f(\sigma_a)$, and $\epsilon_q = g(T_{max})$ and assuming the total strain ε_t is equal to the irreversible strain limit ε_{irr}, $T_{\text{allowable}}$ is expressed as a single-variable function of σ_a ($T_{\text{allowable}}(\sigma_a)$). For Ag/Bi-2212 wires, the detailed shape of $T_{\text{allowable}}(\sigma_a)$ does not depend on magnetic field because neither their strength nor their $I_c(\varepsilon)$ depend on magnetic field. ϵ_t for all experimental cases in Figure 5 were calculated, using the stress and strain data in [22,23] and the $\Delta L/L_{T_{max}-4.2K}|_{wire}$ data in [19],and it varies from 0.42%

to 0.55% (Figure 6), consistent with the ε_{irr} of 0.4-0.6% obtained by measurements of the strain dependence of I_c and further validating the strain model.

The decrease of $T_{allowable}$ with increasing σ_a is intuitively not surprising. The detailed shape of $T_{allowable}(\sigma_a)$ is important, however, because it dictates the balance between the field generation efficiency of a magnet, which increases with increasing operating current and stress, and the safety of the magnet, which decreases with decreasing $T_{allowable}$. It is apparent from Figure 5 that if a Bi-2212 magnet is designed to operate at a σ_a of 120 MPa, 80% of the stress limit, with a T_{max} during a quench designed at 300 K, following the conventional wisdoms, the magnet will likely fail during the first quench. Designing a Bi-2212 magnet to work at a stress of >120 MPa (the yielding stress of Bi-2212 wires is about 110 MPa.) will be a significant risk because during the quench protection the hot spot temperature needs to be kept well below 280 K, which is not an easy task considering that the quench detection is not easy due to the slow normal zone propagation and that the hot spot temperature may exceed 100 K before detection [12,14]. Yet this does not rule out operating a Bi-2212 magnet in the stress range from 120 MPa to 150 MPa because upon quench detection, the magnet current is forced to go to zero, thereby reducing σ_a and effectively raising $T_{allowable}$. The fate of the magnets will therefore reside on the competition between the increase of the hot spot temperature and the increase of the $T_{allowable}$. If the hot spot temperature as a function of time, $T_{max}(t)$, exceeds the maximum allowable temperature $T_{allowable}(\sigma_a(t))$, the magnet will degrade like that in [24].

Note that the detailed shape of $T_{allowable}(\sigma_a)$ depends on the strength of the composite superconductor and the strain dependence of its critical current. The fast decrease of $T_{allowable}$ with increasing σ_a above 120 MPa is a result of the wire starting to plastically deform. Therefore, to increase $T_{allowable}$, one can increase either ε_{irr} or the Young's modulus and/or the yielding stress of the Bi-2212 wire by, for example, using an alternative sheath material such as Ag-Al [25,26].

Together with our earlier investigation [11], this work confirms that the quench induced I_c degradation in Bi-2212 round wires is driven by axial strain. This conclusion seems to be valid for other strain sensitive, multifilamentary wires including Cu/Nb_3Sn wires, Ag/Bi-2223 tapes with or without metal cladding, and MgB_2 tapes and wires (note that REBCO coated conductor has a multilayered thin film structure that more likely fails due to delamination), and thus provides a simple method for estimating the margin to degradation during a quench for superconductors within high-field magnets quantitatively.

Conclusions

This work provides an understanding for avoiding catastrophic degradation of composite superconductors within superconducting magnets due to a quench. $T_{\text{allowable}}(\sigma_a)$ has a clear physical significance and engineering values for magnet design. We introduce a method for measuring $T_{\text{allowable}}(\sigma_a)$ and demonstrate its use using high current density Bi-2212 round wires. We further show that $T_{\text{allowable}}(\sigma_a)$ can be estimated using a strain model from the strain dependence of I_c and the stress-strain data of composite superconductors. While the results shown here are derived from Bi-2212 magnets, the insights and the approach developed are generally applicable for other strain-sensitive technical superconductors including Nb_3Sn, MgB_2, Bi-2223, and REBCO coated conductors.

Acknowledgements

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List of Figures

Figure 1:

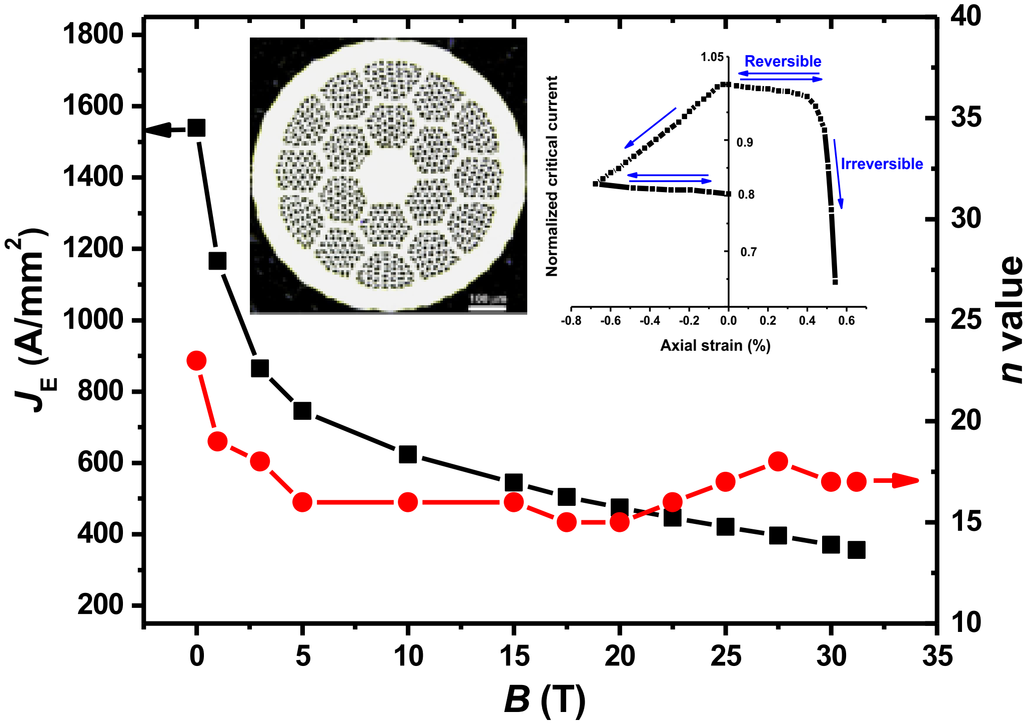

1800
1600
1400
1200
1000
800
600
400
200
J_E (A/mm^2)
0
5
10
15
20
25
30
35
B (T)
40
35
30
25
20
15
10
n value
Normalized critical current
Axial strain (%)
Reversible
Irreversible
1.05
0.9
0.8
0.7
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6

Figure 2

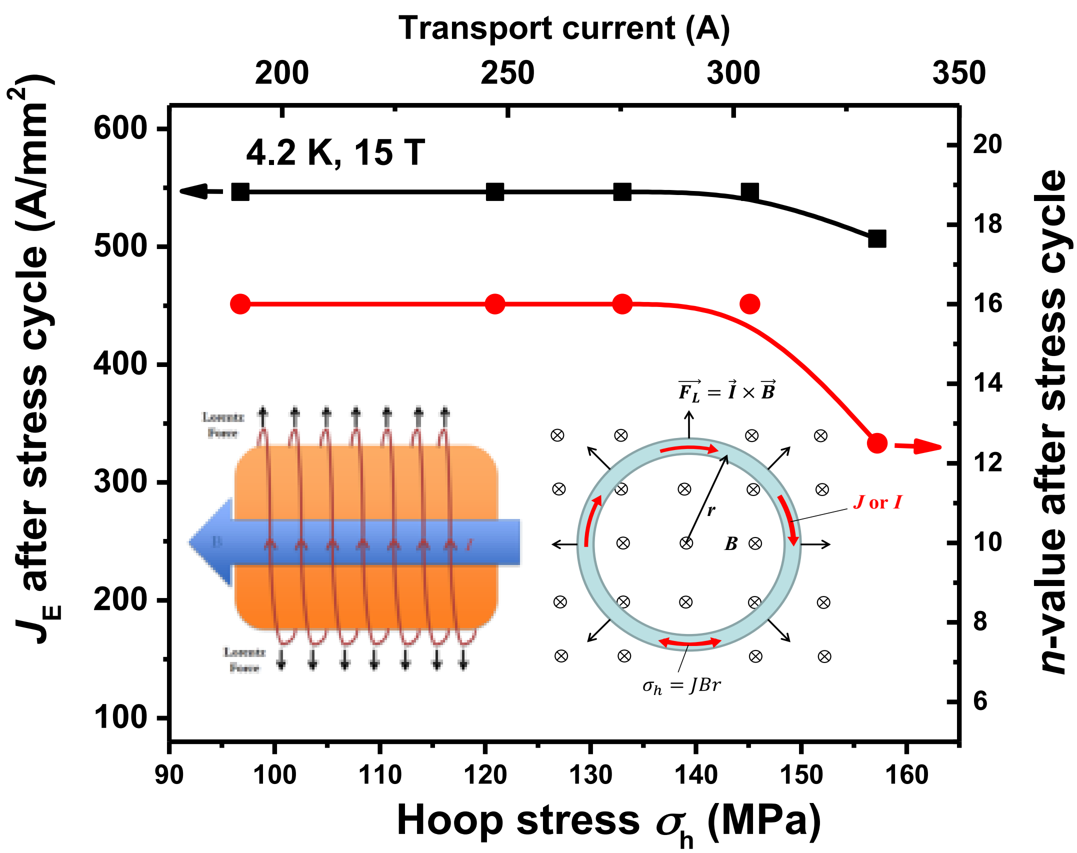
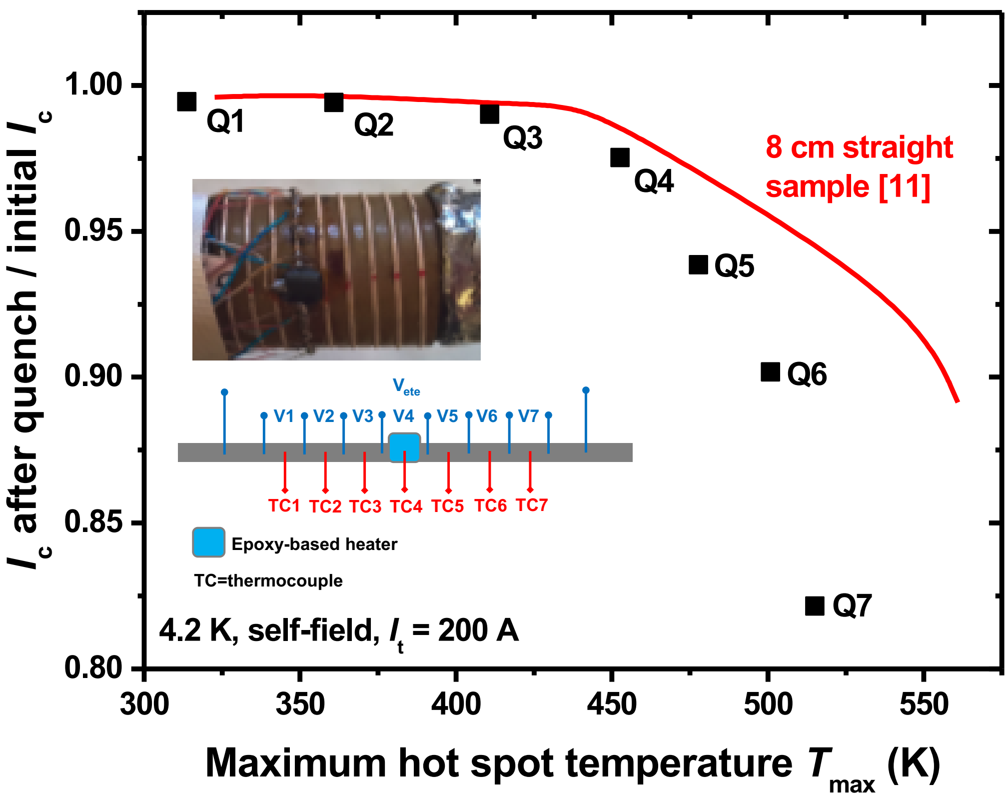
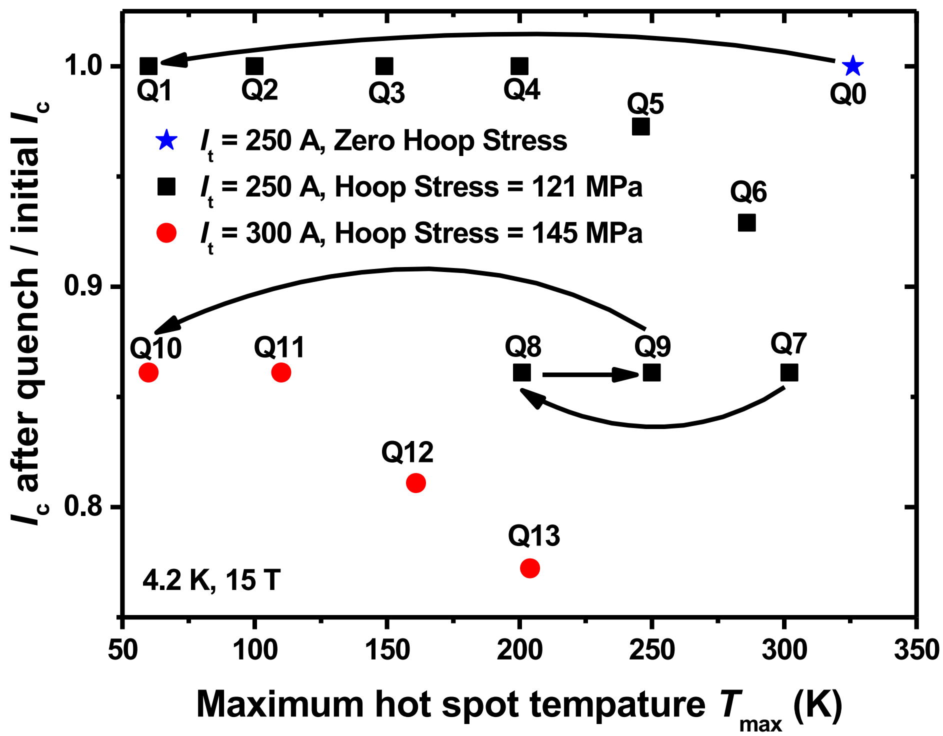

Transport current (A)
200
250
300
350
600
500
400
300
200
100
20
18
16
14
12
10
8
6
90
100
110
120
130
140
150
160
4.2 K, 15 T
J_E after stress cycle (A/mm^2)
n-value after stress cycle
Hoop stress σ_h (MPa)
$\vec{F_L} = \vec{I} \times \vec{B}$
r
B
J or I
$\sigma_h = JBr$

Figure 3



I_c after quench / initial I_c
1.00
0.95
0.90
0.85
0.80
Q1
Q2
Q3
Q4
Q5
Q6
Q7
8 cm straight sample [11]
V_{ete}
V1 V2 V3 V4 V5 V6 V7
TC1 TC2 TC3 TC4 TC5 TC6 TC7
Epoxy-based heater
TC=thermocouple
4.2 K, self-field, I_t = 200 A
300 350 400 450 500 550
Maximum hot spot temperature T_{max} (K)

Figure 4



1.0
0.9
0.8
Q0
Q1
Q2
Q3
Q4
Q5
Q6
Q7
Q8
Q9
Q10
Q11
Q12
Q13
I_t = 250 A, Zero Hoop Stress
I_t = 250 A, Hoop Stress = 121 MPa
I_t = 300 A, Hoop Stress = 145 MPa
4.2 K, 15 T
I_c after quench / initial I_c
50
100
150
200
250
300
350
Maximum hot spot tempature T_{max} (K)

Figure 5

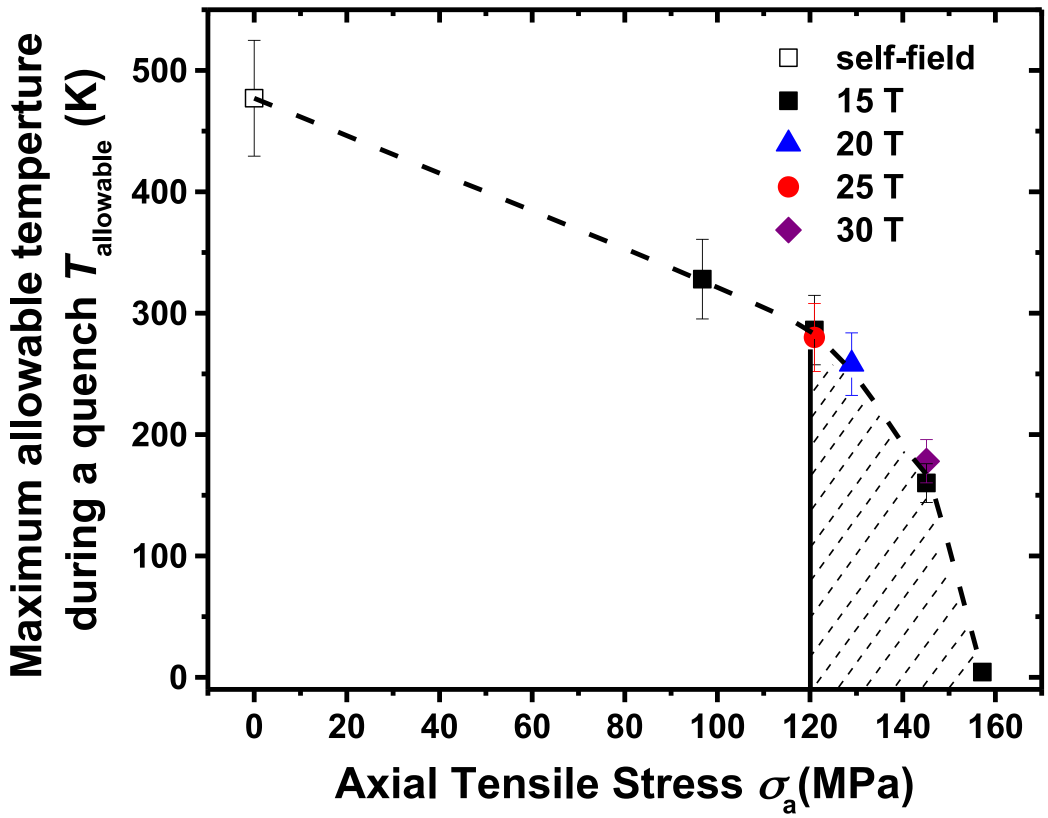
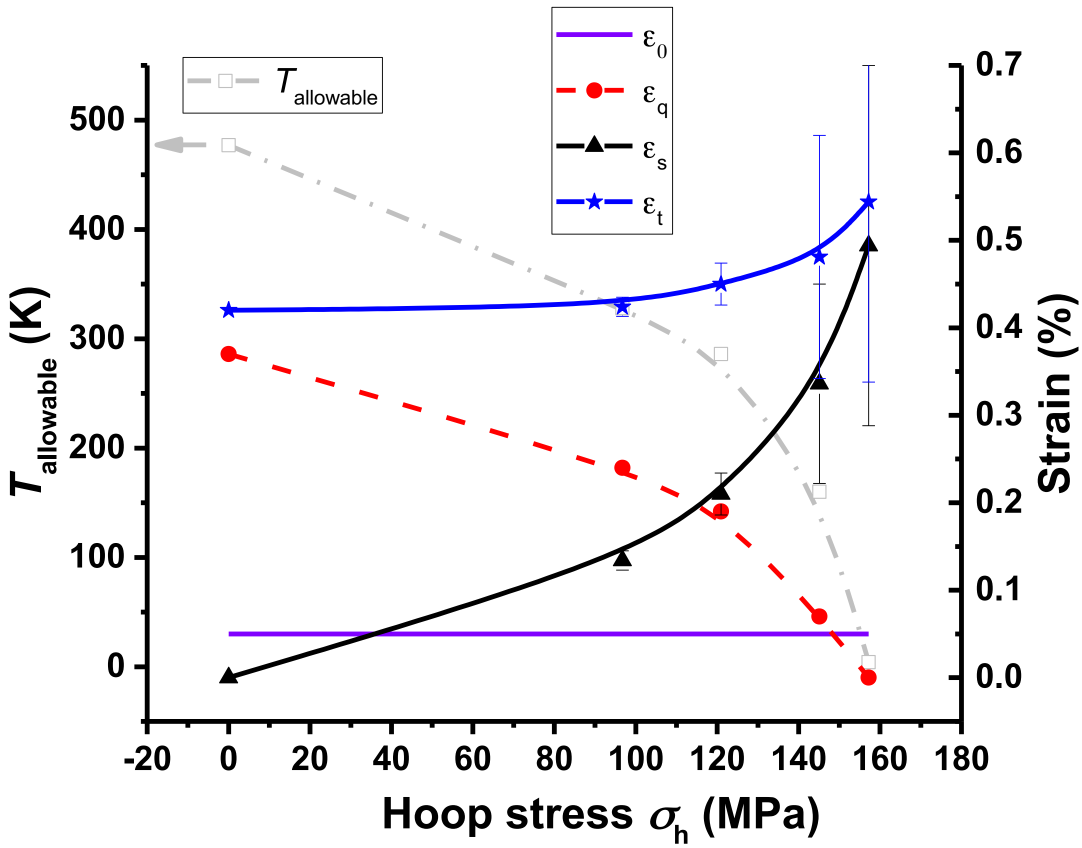

self-field
15 T
20 T
25 T
30 T
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
Maximum allowable temperture during a quench $T_{allowable}$ (K)
Axial Tensile Stress σ_a(MPa)

Figure 6:


T allowable
ε0
εq
εs
εt
T allowable (K)
Strain (%)
Hoop stress σh (MPa)
500
400
300
200
100
0
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-20
0
20
40
60
80
100
120
140
160
180